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DEVELOPMENT AND IN-PILE PERFORMANCE OF SOME BR2 IRRADIATION RIGS

by

P. von der HARDT

1967

Report prepared at the CEN

Centre d'Etude de l'Energie Nucléaire, Mol - Belgium

Association No. 006-60-5 BRAB

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This report concerns the development of some of the capsule type irradiation devices (rigs) built for BR2, and irradiated in the period between 1965 and 1967.

Most of the work described has been performed and/or coordinated by the CEN Technology Department.

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KEYWORDS

RESEARCH REACTORS
MATERIALS TESTING
IRRADIATION
IN PILE LOOPS
DESIGN
PERFORMANCE
FABRICATION

BR-2
Capsules

Table of Contents.

Key to the Tables.

<u>Key to the Figures.</u>

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DEVELOPMENT AND IN-PILE PERFORMANCE OF SOME BR2. IRRADIATION RIGS

1. Summary. (*)

The high-flux materials testing reactor BR2 in MOL (Belgium) can satisfy a very large number of experimental requirements due to its conception, and especially its compact core design and to the easy handling of its testing equipment.

Between the experimenter's request, i.e. submit specimens of future reactor materials to environment conditions similar to those expected in power reactors and the actual irradiation in pile there is, however, a large field of technological problems : design, development and manufacture of the appropriate irradiation device.

This report concerns the development of some of the capsule type irradiation devices (rigs) built for BR2, and irradiated in the time between 1965 and 1967.

Most of the work described has been performed and/or coordinated by the C.E.N. Technology Department.

2. BR2 as a Materials Testing Reactor.

2.1. The Reactor.

The Belgian Engineering Test Reactor (BR2) is operated on the basis of the contract of association between the Centre d'Etude de l'Energie Nucléaire (C.E.N.) and the European Atomic Energy Community (EURATOM).

BR2 is designed as a high-flux materials testing reactor using highly enriched MTR - type fuel, light water as coolant and moderator, and beryllium as moderator and reflector. For a detailed description of the reactor and is connected laboratories, see ref. (1).

The reactor has been working for more than four years (ref. (2) & (3).
Since November 1965, the core configuration shown on fig. 1 has been used, featuring 28 fuel elements and 10 control rods.

(*) Manuscript received on August 1, 1967.

BR2 is usually operated in 28-days-cycles which are made up from two equal running periods and two unequal shut-down periods, according to the following scheme :

Main shut-down for fuel change, maintenance and work on the experimental equipment	5 days
First running period	10,5 days
Small shut-down for fuel change	2 days
Second running period	10,5 days
Total cycle	28 days.

2.2. In-Pile Irradiation Facilities.

Although substantial thermal neutron fluxes (up to 5.10^{13} n/cm^2 s) can be met outside the reactor vessel, the more specific BR2 irradiation experiments take place within the beryllium matrix.
With the core configuration as represented on figure 1, the in-pile irradiation facilities are as summarized in table 1 hereafter.

Table 1.

Summarized BR2 In-Pile Irradiation Facilities.

Region	Number of positions	Position Designation	Required Irradiation Device O.D. (mm)	Unperturbed Neutron Flux at 57 MW Gross Power Output (10^{14} $n/cm^2.s$), maximum. thermal	fast (above 0,1 MeV)
Core	28	Fuel Element	17,4 to 34,0 (standard). Larger rigs can be accommodated in special fuel elements.	2 to 6,0	1 to 5,0
Reflector	10	Be-Matrix, 2" hole	up to 46,0	1,0	below 0,01
	26	Be-Matrix, standard	29,5 to 80,6	1,7 to 5,6	0,01 to 1,1
	5	Be-Matrix 8" hole	up to 200,2	1,0 to 10	0,01 to 1,7

The nuclear data quoted are typical figures, and may vary for the same hole from one cycle to another, due to different core loading.

The nuclear heating induced into aluminium by absorption of the mixed reactor radiation is between 6 and 17 W/g for the core region, and between 1 to 8 W/g for the reflector.

2.3. General Aspects of BR2 Irradiation Equipment.

2.3.1. Geometrical Requirements.

The following paragraphs only apply to in-pile rigs fixed to the reactor vessel top cover (standard case), but analogue principles are valid for in-pile sections penetrating through the lower cover.

BR2 rigs are made up of four main components :

- the specimen carrier section, housing the material specimens to be irradiated, as well as "instrumentation" (if any) : thermocouples, gas leads, flux monitors, heater elements, etc.
- the lower extension piece ("nose guide"), which has three functions : 1. to guide the rig during its introduction into the irradiation channel, 2. to centre it in its irradiation position, 3. to assure water-flow continuity over the total core height.
- the upper extension piece (suspension tube) connecting the specimen carrier section to the rig head in the reactor top cover,
- the rig head, which has several functions : 1. positively fix the rig in radial and axial direction by locking it to the access hole in the reactor pressure vessel top cover, 2. to assure leak tightness of the pressure vessel by plugging the access hole, 3. to carry the external rig handling device ("lifting eye"), 4. (in the case of an "instrumented" rig) to accommodate the connections for thermocouples, gas lines, etc.

The lengths of the four main components are usually as follows :

- specimen carrier section	100 to 900 mm
- lower extension piece	150 to 500 mm
- upper extension piece	4.000 to 4.400 mm
- rig head	400 to 1.000 mm
Total irradiation device	5.400 to 6.000 mm.

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BELGIAN ENGINEERING TEST REACTOR BR2.
SCHEMATIC CORE LOADING DIAGRAM.

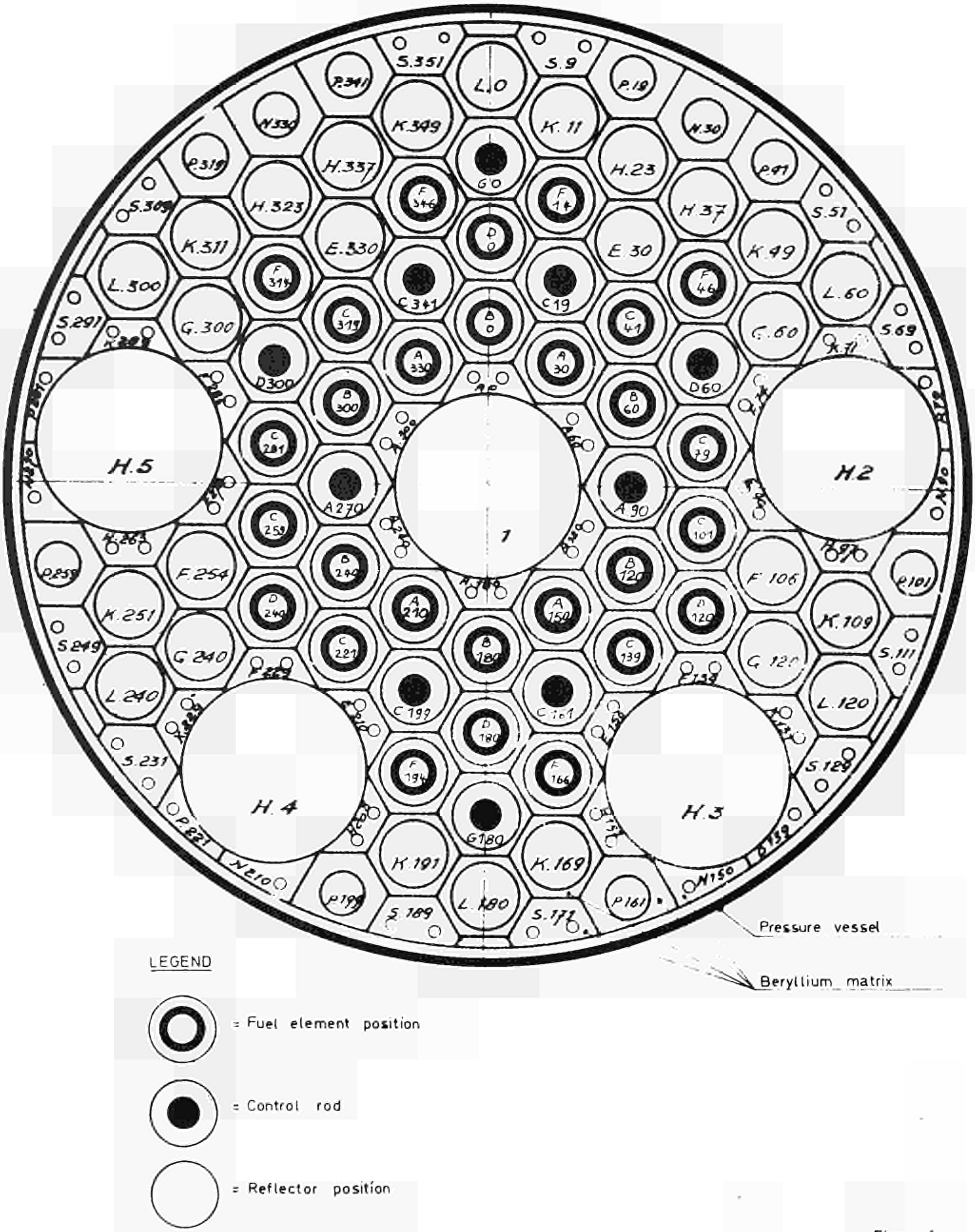

Figure 1

Since the outer diameters of all components (except rig heads) are those indicated in table 1, i.e. normally between 17 and 50 mm roughly, it can be seen that the typical BR2 rig has the appearance of a long, slender cylindrical body, and that 70 to 90% of the total length are occupied by auxiliary extension pieces.

2.3.2. Design of the Specimen Carrier Section.

The specimen carrier design procedure can be represented by the following simplified scheme :

- Design the specimen (specimen assembly) surrounded by the smallest possible O.D. containment tube ("thimble") according to table 1.
- Fill the interspace with matter selected from thermal calculations and from practical considerations, such as compatibility, machining and welding facilities, price, etc.
- Locale "Instrumentation", if requested.

The utilization of standardized specimen carriers in BR2 is limited to irradiation experiments without stringent specifications concerning the irradiation temperature or to series of very similar specimens. The high power rating, induced into all materials by nuclear heating and into fissile material due to the high thermal neutron flux available, usually asks for the design of carrier sections which are "taylored" to their specific specimen.

2.3.3. Rig Manufacture.

The choice of structural materials is rather limited, both for compatibility and technological reasons. Stainless steel of the AISI 304 or 316 series is preferred for all welded structures up to 800°C working temperature. Aluminium and aluminium alloys are used for temperatures below 300°C, whenever thick-walled structures are required and where the problems of high grade aluminium welding do not occur or can be solved by electron-beam technique.
Niobium and graphite are used as current high temperature structural material and liquid alcali metals as heat transfer medium.

In view of the hazards involved and of the high cost of in-pile experiments, the principle adopted is that the best technological process available is just good enough for rig making.

Hence, extensive testing goes along with the manufacturing operations in an alternating rhythm, i.e., every relevant assembly operation is first tested before the next step is done. A standard set of tests carried out would be e.g. on a specimen carrier represented as a tube closed by two welded end caps :

- dimensional control of all pieces prior to assembly, material certificates being on hand, dimensional control after welding,
- radiographic control of the assembly and the welds,
- external and (if necessary) internal pressure testing, to 1,5 times the maximum possible operating pressure,
- leak test, in some cases after degreasing and pickling, using the helium mass spectrometer method.

New joining techniques by welding or brazing are first examined by destructive testing of dummy assemblies before applying them to the final piece.

Thermocouples and electrical heater elements are tested for loop and insulation resistance as supplied, and further during the different stages of the rig assembly.

The standard BR2 rig manufacturing can be represented by the following programme scheme :

- Overall layout and design, detail design,
- Machining, control and cleaning of the rig components,
- Assembly and testing of the specimen carrier,
- Assembly of the upper extension piece (suspension tube),
- Assembly and testing of the rig head and its service line connections,
- Mounting of the lower extension piece,
- Overall and final control.

2.3.4. Cost and Time Requirements.

Although prices and delays of in-pile equipment can vary largely according to the large variety of design principles, two handy "rule-of-thumb" formulae can be given from experience gained in BR2. They say that the relative cost between

- an "uninstrumented" capsule-type irradiation device (rig),
- an "instrumented" rig, and
- a loop in-pile section

are :

<u>1 : 10 : 100</u>,

./.

and that the relative design and manufacturing times of these classes of equipment are :

$1 : \sqrt{10} : 10.$

Approximate absolute figures are given in table 2 below.

Table 2.

Cost and Time Requirements of BR2 In-Pile Equipment.

Class of In-Pile Equipment	"Order-of-magnitude" - Figures	
	Manufacturing Cost (US $)	Design and Manufacturing Time (Months)
"Uninstrumented" Rig	1.000	4
"Instrumented" Rig	10.000	13
Loop (in-pile section)	100.000	40

To complete it should be kept in mind that the cost of the out-pile control equipment for "instrumented" rigs and loops may be as high as one to five times the price of the corresponding in-pile section.

3. Development and Performance of Some Specific Rigs.

3.1. Introduction.

In the following paragraphs, the history of several BR irradiation rigs is summarized. No detailed description will be given of the corresponding out-pile equipment (if any).

3.2. Uninstrumented Rigs.

3.2.1. General.

Irradiation devices with no service lines (thermocouples, gas tubes, etc.) running from the specimen carrier up to the rig head, are referred to as "uninstrumented rigs".

./.

The advantage of using such equipment for material testing irradiations lies in the simplicity of the design resulting in both low cost and short assembly time.

Information on the irradiation temperature has to rely entirely on thermal calculations. Melting wire temperature detectors have been tried (see paragraph 3.1.4.) but are not considered to be reliable.

Accurate information can be obtained on integrated thermal and/or fast flux using activation detectors.

3.2.2. UO_2 Rods in NaK.

3.2.2.1. Scope of the Experiment.

Two UO_2 rods containing slightly enriched fuel had to be irradiated to about 9.500 MWd/t burn-up, in a thermal neutron flux of roughly 1×10^{14} n/cm^2 s.

3.2.2.2. Solution.

Due to the high power density on the rod cladding surface, an irradiation in direct contact with the reactor primary water could not be considered (burn-out hazard). Hence, a single-walled can was designed (see figure 2) keeping the rod in a sodium-potassium eutectic bath. The two cans were placed into a open-type Al basket.

3.2.2.3. Thermal Characteristics.

The rig was irradiated in three campaigns with increasing flux values. The steps in the neutron flux were achieved by core configuration modifications and choice of the irradiation position, resulting in the nuclear parameters as listed in table 3.

Table 3.

Nuclear Parameters of the UO_2-NaK Rig.

Campaign Nr.	Perturbed (effective) thermal neutron flux in the rods (10^{14} n/cm^2 s)	Maximum fission power output per unit length (W/cm)	Irradiation duration (BR2 cycles)
1	0,45	325	3
2	1,04	658	4
3	1,25	582	2

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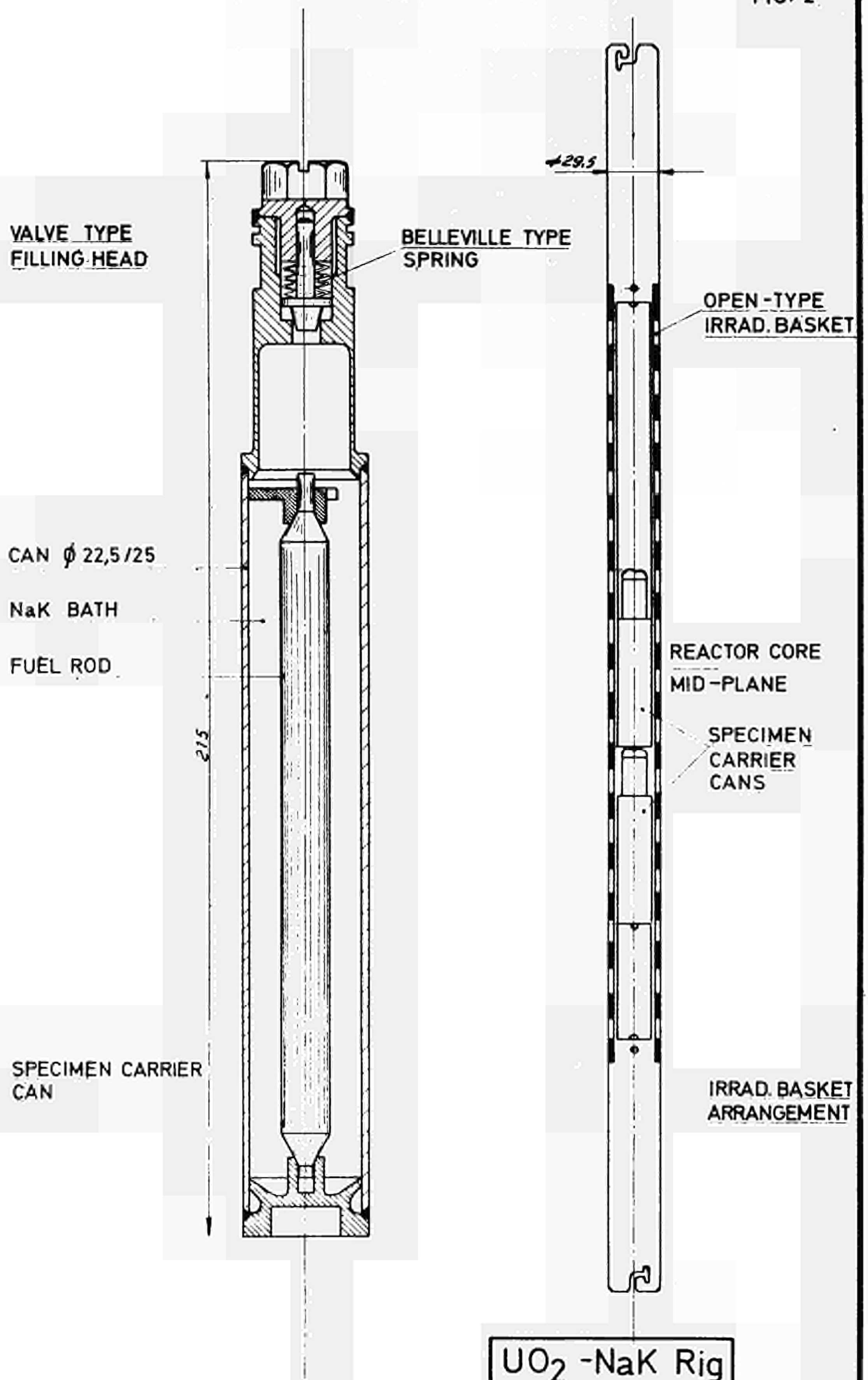
FIG: 2



UO_2 -NaK Rig

Taking into account the nuclear heating by absorption of mixed reactor radiation in the rig components (between 0,5 and 2 W/g in the selected reflector position), one calculates the following minimum and maximum temperatures (°C) :

	Minimum	Maximum
Stainless steel can, exterior	70	90
interior	105	160
NaK bath, mean temperature	190	325
Fuel rod cladding surface	275	500

(Primary water bulk temperature = 50°C).

3.2.2.4. Rig Manufacture.

In view of the potential hazard of a NaK-water reaction, particular care was taken to build a strong and technologically "healthy" can (specimen carrier).

To this end, argon-arc welding on a welding machine was chosen, assuring exactly reproducible parameters, such as welding speed and arc length, as well as overall inert atmosphere. Three complete test units were fabricated in order to find out the optimum welding parameters, and the welds were examined by X-ray and then by micrographs. Upon adjustment of the parameters and of the weld design, five more test units were made up. X-raying and micrographic examination yielded satisfactory results (see figure 3).

Four test units were then welded with the parameters chosen and tested with X-rays and helium leak probe. They were then pressurized with water to 400, 450, 480 and 500 kg/cm^2. After drying in a 150°C furnace, the subsequent helium test showed no leakage. The test cans were then further pressurized up to bursting which occured at 560 ± 10 kg/cm^2. In all cases, the failure was located in the Ø 22,5/25 mm tube whereas the welds were unaffected.

Another test can was filled with 15 cm^3 NaK after assembly, welding and testing, using the valve-type filling head. It was then kept at 400°C, under protectiv atmosphere, during a total period of 28 days with intermediate thermal cycling. After disposal of the NaK filling and dismounting, the welds were examined by micrography. No defects were to be found.

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For the acceptance of the fuel rods, six dummy assemblies of cladding and end plugs were submitted to the following test programme :

- ultrasonic check on wall thickness and defects,
- dimensional control,
- degreasing and pickling,
- exterior pressure and helium leak test,
- weld X-raying.

Four of the assemblies were pressurized up to bursting and specimens were taken for chemical material analysis. Finally, all welds were sectioned and checked by macrographic and micrographic examination.

The two fuel rods to be irradiated were checked using the above-mentioned non-destructive methods and, in addition, by ultra-violet light check on surface cracks and checks on the homogeneous distribution of fissile material.

The two specimen carrier cans were finally assembled using the methods approved after the above-mentioned preliminary tests, together with a third witness can containing a dummy rod. Testing comprised weld and total X-ray photographs, autoclave pressurizing and final helium leak probes. One finished can is shown on figure 4.

3.2.2.5. Dosimetry.

Prior to the irradiation of the completed rig, a nuclear model was made up simulating the characteristics of the rig. The model specimen carrier can contained two aluminium shells (replacing the NaK bath) inside a 22,5/25 mm stainless steel tube and a ∅ 8/10 mm "cladding" tube filled with Al_2O_3 - boron mixture to simulate the fuel. Two rows of four Co wire monitors were placed against the "cladding" tube for integrated thermal flux scanning.

The nuclear model was irradiated during a short-time low-power run of the reactor. The analysis of the Co monitors yielded the overall "self shielding" coefficient of the rig, i.e. the ratio of the perturbed mean flux in the fuel rods over the unperturbed flux in the considered irradiation position. This ratio was found to be 0,6.

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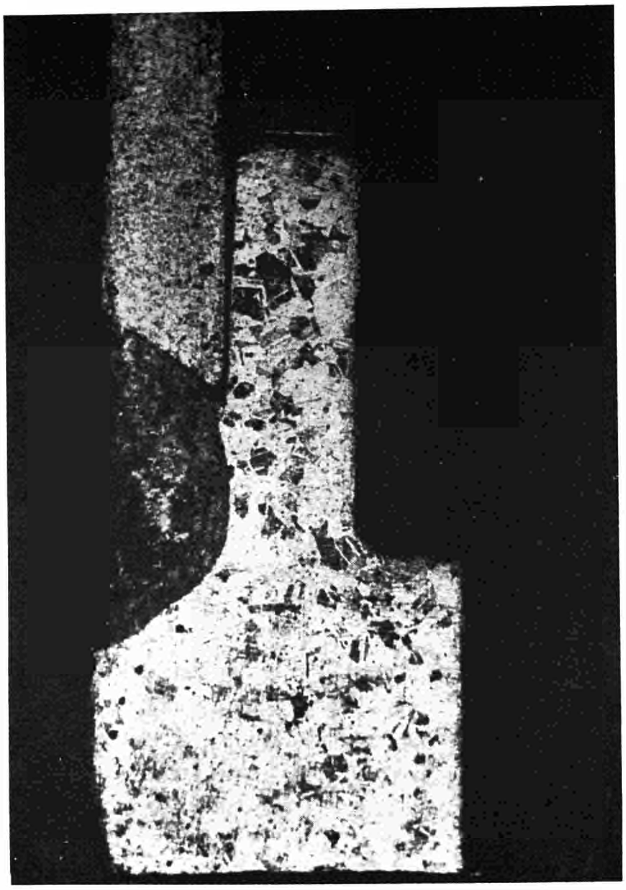


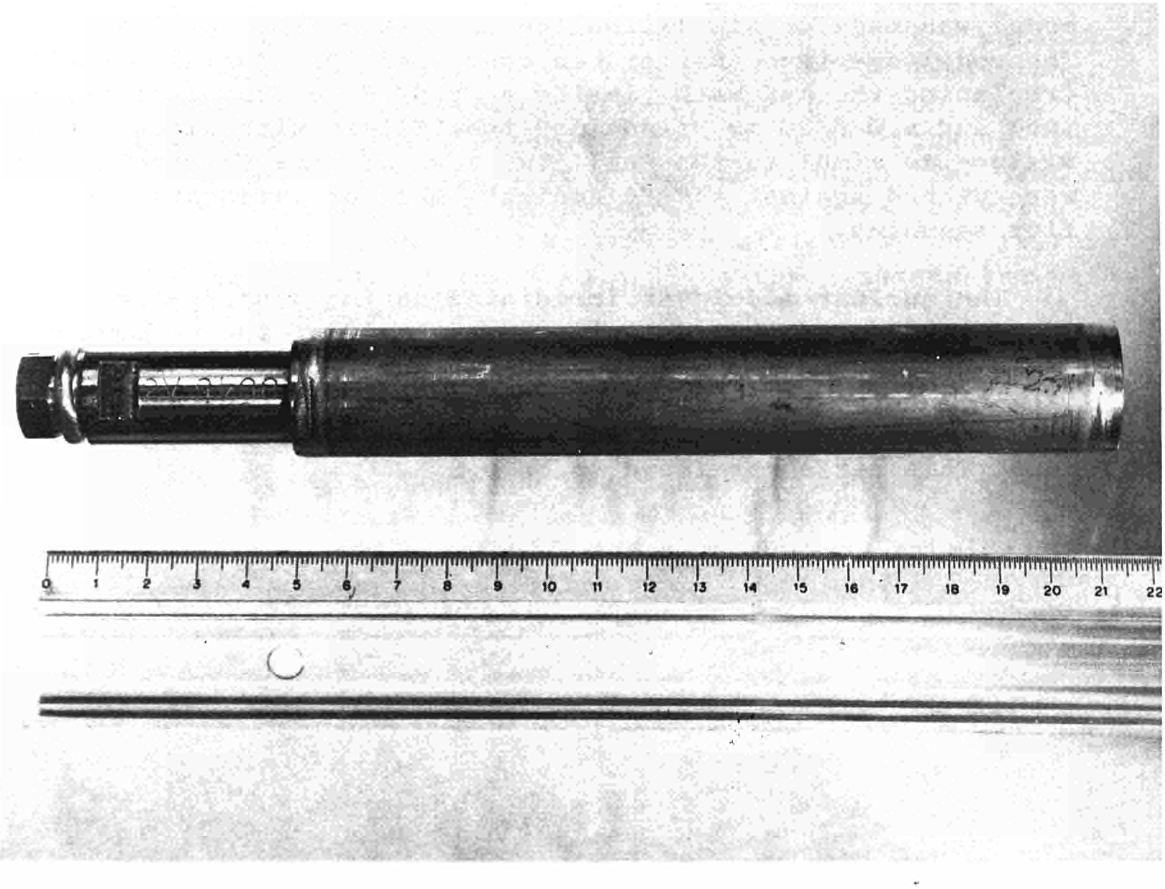
Micrograph of a Test Weld

Figure 3.

UO_2 - NaK Rig

Specimen Carrier Can

Figure 4.



3.2.2.6. Irradiation.

The rig was irradiated in a BR2 reflector position according to the programme summarized in table 3. A second in-pile dosimetry was taken between the first and the second campaign in order to assess the altered nuclear parameters.

A total irradiation time of 9 BR2 cycles (roughly 9 months) was necessary to achieve a calculated burn-up of about 9.000 MWd/t.
Inspection after irradiation showed that both cans and fuel rods were in excellent condition with no visible change as compared to the pre-irradiation appearance.

3.2.2.7. Safety.

Extensive calculations had been made to assess the possible consequences of a can leak with following NaK-water reaction.
It could be proved that damage to the reactor due to a complete can breakdown would not be likely to occur, but that even small quantities of NaK ejected into the reactor primary water system would effect the overall pH value and the water resistance. Moreover, the increased contents in radioactive Na 24 would be detected by appropriate means.

The latter phenomenon was used for a leak detecting device counting the primary water Na 24 activity through two independent chains with scintillation counter and monochannel analyser.
Leaks of about 1 cm^3 of activated NaK could have been detected with 5 minutes dead time.

3.2.2.8. Post-Irradiation Work.

Upon recovery of the two rods in the BR2 Dismantling Cell, a large number of post-irradiation examinations were carried out, comprising dimensional checks, fission gas analysis, macrographic and micrographic controls, etc.

Cs-137 analysis yielded a burn-up of 8.200 MWd/t which is in satisfactory agreement with the above-mentioned calculations.

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3.2.3. UO_2 Rods in an Open Basket.

3.2.3.1. Scope of the Experiment.

Three Zr-2 clad natural UO_2 rods had to be irradiated to about 2.500 MWd/t burn-up, in a thermal neutron flux of roughly 1,5 x 10^{14} n/cm2 s.

3.2.3.2. Solution.

The rods were mounted, in a triangular array, into an open irradiation basket with direct cooling by the reactor primary water.

3.2.3.3. Rig Manufacturing.

For the fuel rods, the same tests were applied as described in paragraph 3.2.2.4. of this report.

The assembled basket was submitted to dimensional controls as well as to X-ray examinations of the two main assembly welds.

3.2.3.4. Irradiation

The rig was irradiated in a BR2 reflector position during 4 reactor cycles, with thermal neutron fluxes between 1,6 and 2 x 10^{14} n/cm^2 s, leading to a calculated unit length power output between 400 and 500 W/cm. No nuclear model dosimetry had taken place, so that all figures were based on previous measurements in the reflector and upon calculations. The rig "self-shielding" coefficient was probably underestimated by about 20% since the post-irradiation Cs-137 analysis yielded only a burn-up of 1.900 MWd/t, as against a calculated figure of 2.500 MWd/t. Hence, a more realistic estimation leads to a unit length power output between 320 and 400 W/cm.

The fuel rods were recovered in excellent condition and showed no visible change as compared to the pre-irradiation appearance.

3.2.4. The Graphite-B_4C Rig.

3.2.4.1. Scope of the Experiment.

B_4C particles with graphite coating had to be irradiated up to 80 ± 10% consumption of the B 10 isotope. The particle temperature should be between 600 and 1000°C during irradiation.

./.

3.2.4.2. Solution.

An irradiation device was designed and calculated for loading into a BR2 fuel element position. The boron carbide particles were loaded into a graphite matrix with 8,6 mm O.D.
The specimen carrier can surrounding the matrix had 10,6 mm I.D. and 12,0 mm O.D., leaving a 1 mm helium gap towards the matrix. A 0,2 mm nitrogen gap was left between the carrier can and an aluminium filler piece, press-fitted into the ∅ 16,0/17,4 mm outer tube ("thimble").

The rig zones are resumed as follows :

Graphite matrix	∅ 8,6 mm	helium gap
Carrier can (stainless steel)	∅ 10,6/12,0 mm	nitrogen ga
Al filler piece	∅ 12,4/16,0 mm	
Outer tube (stainless steel)	∅ 16,0/17,4 mm	

3.2.4.3. Thermal Characteristics.

The main heat source of the rig, bringing the matrix temperature up to above 600°C, is the carrier can, heated up by the reactor mixed radiation (nuclear heating) and isolated by the N_2 gap.

The calculated temperature profile is shown on figure 5, the consumption diagramme of the B 10 isotope on figure 6.

3.2.4.4. Temperature Monitor.

A melting wire temperature monitor was fitted to the graphite matrix in order to prove that 600°C at least had been obtained under irradiation. Calculations had shown that the high end of the specified temperature range, 1000°C, was not likely to be reached.

Tests have been carried out in order to show the reliability of the monitors. The first series consisted in pure aluminium wires enclosed into 3 mm O.D. quartz ampoules with helium filling.
Six test ampoules (see figure 7) were manufactured, of which four have been heated up to temperatures between 660 and 680°C.

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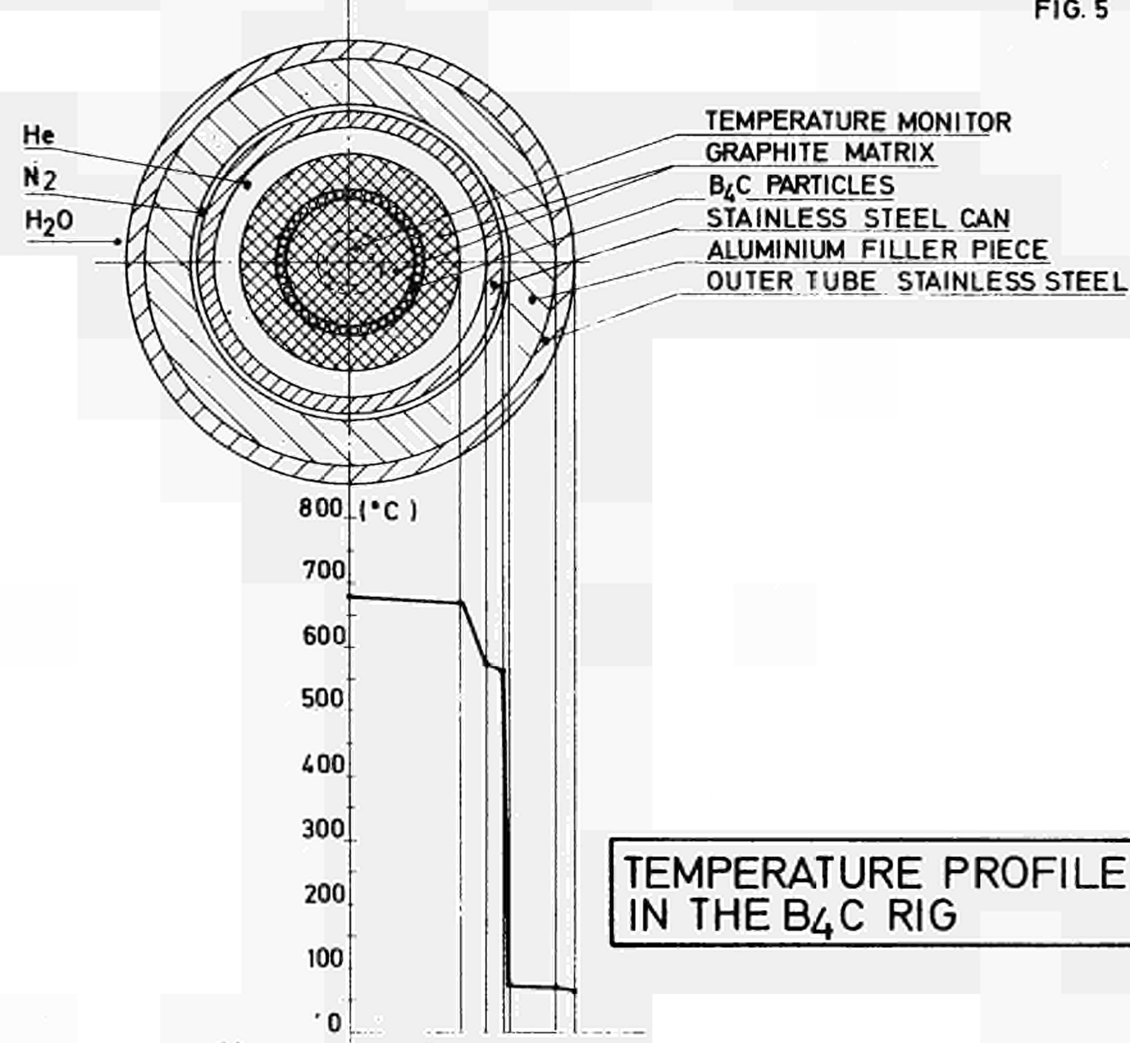
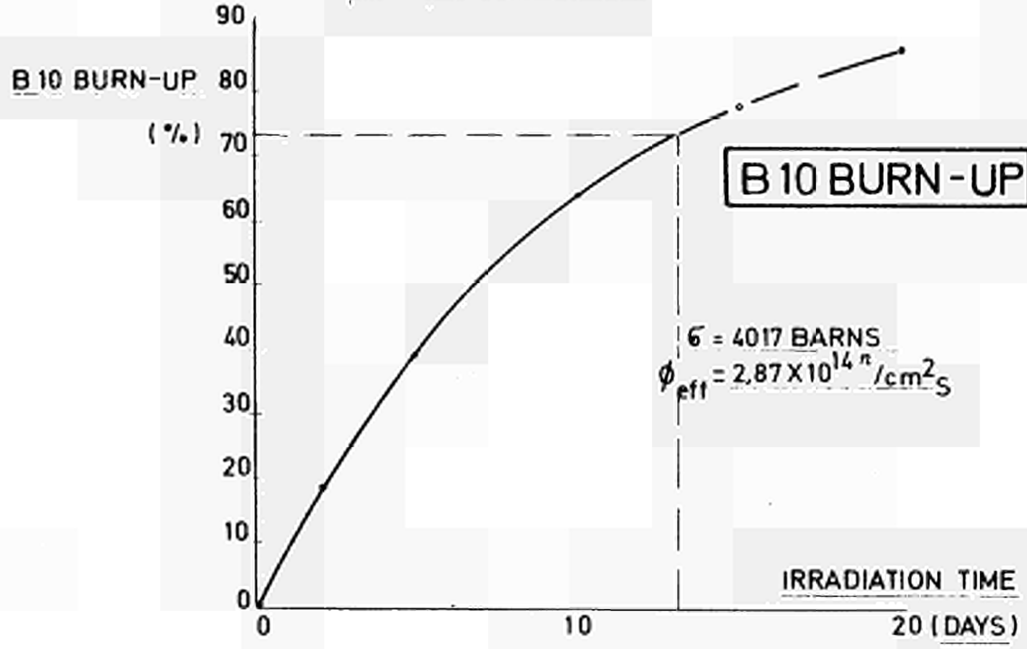
FIG. 5

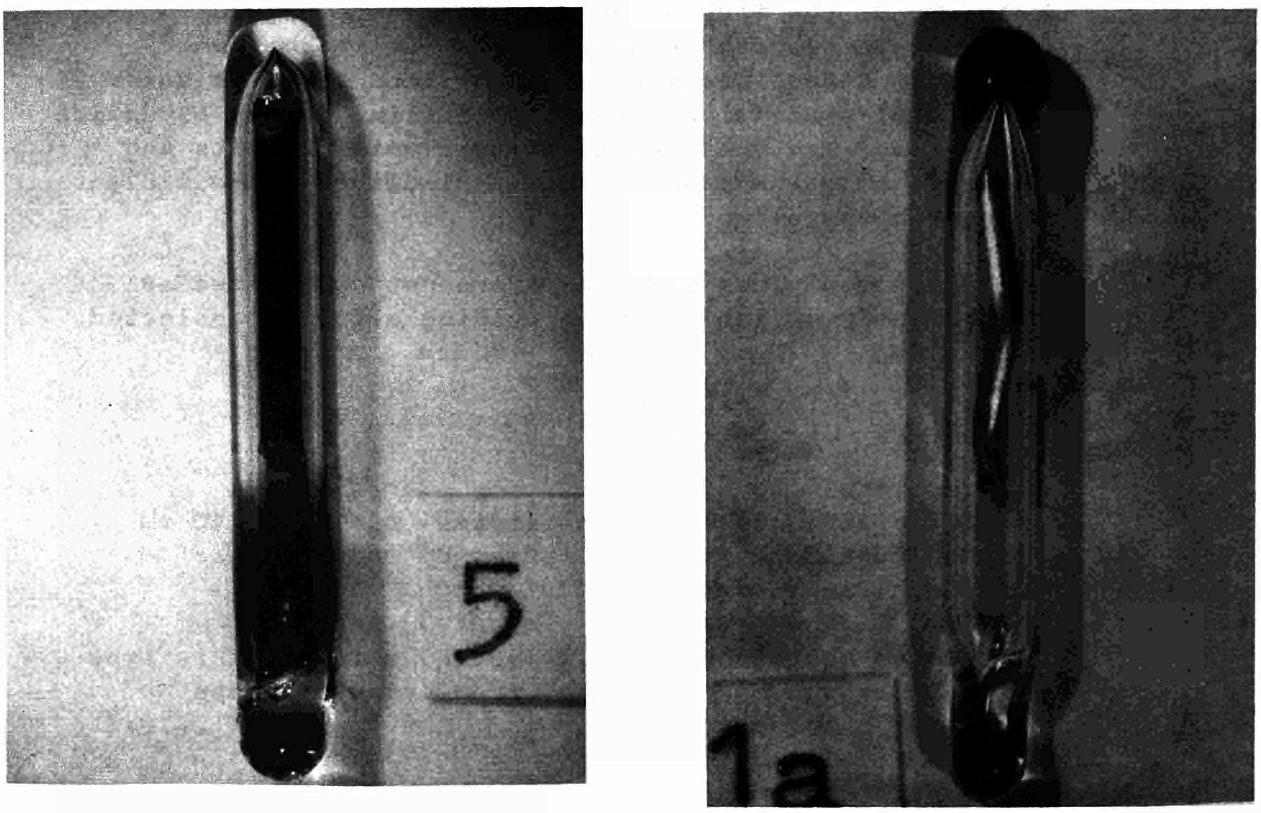


TEMPERATURE PROFILE IN THE B_4C RIG

FIG. 6



B 10 BURN-UP



Test Monitor Ampoule (before furnace run)

Monitor Ampoule for the Irradiation Rig (before irradiation)

Figure 7.

Temperature Monitors for the B_4C Rig.

Enlargement $\approx$ 4x.

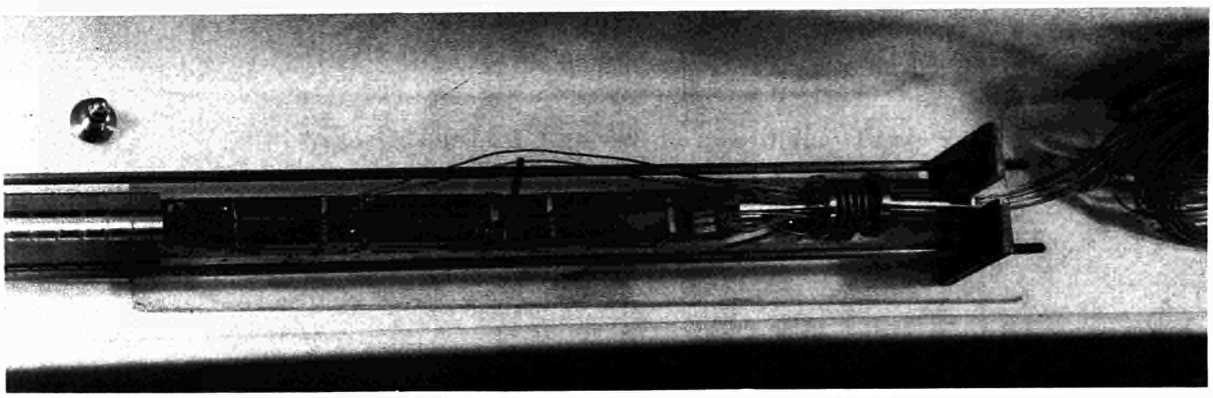


Figure 8.

Assembly Device for the 300°C Steel Rig.

Only two of the four wires seemed to have melted, whereas the two others showed practically the same aspect as before heating. It is assumed that, in spite of careful evacuation and helium filling, heavy oxydation takes place, so that the metallic aluminium melts and solidifies inside a solid Al_2O_3 "cladding" without clear change in shape.

Aluminium wires were therefore not considered as sufficiently reliable, and a welding alloy was selected, containing

45% Ag	17% Zn
16% Cu	22% Cd

melting at 610 to 630°C.
In view of the small wire dimension (Ø 1,5 mm, 10 mm long), thermal neutron absorption by cadmium was considered admissible.

As the tests showed well defined melting, this type of monitors was used for the irradiation rig (see figure 7, photo 1a).

3.2.4.5. Irradiation.

The rig was irradiated during 13,1 days in a BR2 fuel element position. The calculated radial temperature distribution and the effective B 10 burn-up are shown on figures 5 and 6.

Inspection of the temperature monitor after irradiation and rig dismantling showed complete melt-down of the wire.

The effective (perturbed) thermal neutron flux had been measured by means of a standard Co wire integrator.

3.2.5. The Fast Neutron Be Rig.

3.2.5.1. Scope of the experiment.

Five metallic beryllium cylinders of 8 mm diameter and 10 mm length had to be irradiated in a spectrum above the Cd cut-off.

3.2.5.2. Solution.

A rig was designed and built for the irradiation of the targets in a BR2 fuel element position (see figure 9) under a cadmium screen. Natural iron disc monitors of 3 mm diameter and 0,1 mm thickness served as fast neutron integrators.

During the rig mounting, particular care was taken to avoid any contact of the specimens with moisture or organic matter. To this end, the assembly was carried out in a glove box under dry helium atmosphere.

3.2.5.3. Irradiation.

The irradiation took place inside a six-plate BR2 standard fuel element with support tube. With 7,7 days effective irradiation time, the fast neutron dose (E above 1 MeV) achieved was (1,36 $\pm$ 0,02) 10^{20} nvt, corresponding to an average instantaneous flux (above 1 MeV) of 2,04 . 10^{14} n/cm^{2}s. The figures quoted are based on the flux monitor analysis using the Fe 54 (n, p) Mn 54 reaction.

Future fast neutron Be irradiation rigs are under development.

3.3. Instrumented Rigs.

3.3.1. General.

Regardless of the high cost and long development time, in-pile irradiation devices with information on the specimen temperature under irradiation and control of the temperature are required for most of the BR2 materials test experiments.

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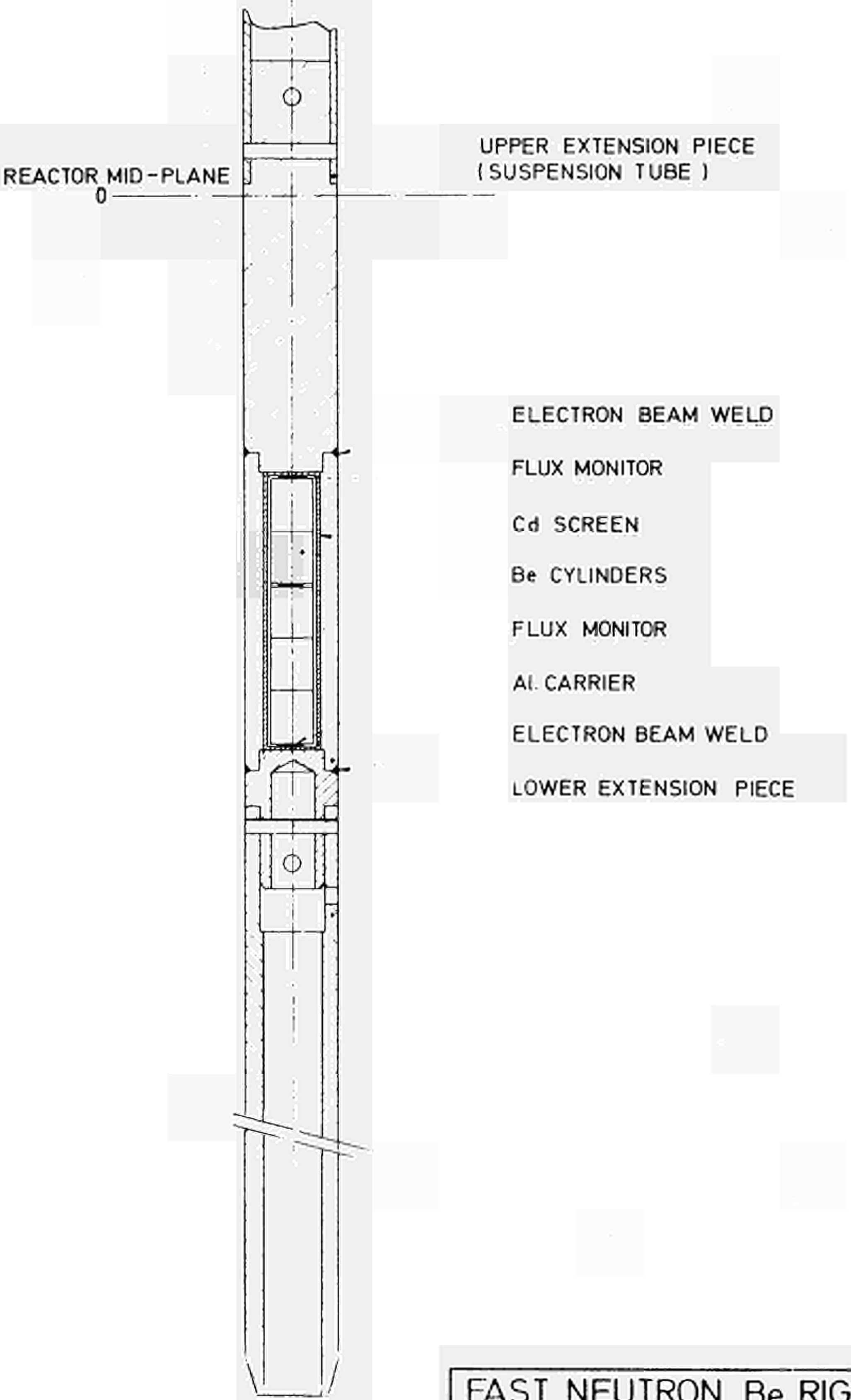
FIG: 9



FAST NEUTRON Be RIG

The reason is mainly that the phenomena of direct or indirect radiation damage caused by fast neutrons in structural materials and/or fission products in fissile materials strongly depend upon the temperature of the specimens under irradiation. Moreover, permanent supervision of the thermal behaviour of the irradiation device helps considerably in judging the safety of the experiment along with possible measurement of other parameters such as pressure, gas activity, flow rates, etc.

For one-dimensional heat transfer problems in cylindrical geometry which can usually be assumed to represent with sufficient accuracy the thermal behaviour of a BR2 irradiation device, the temperature gradient is directly proportional to the radial heat flow multiplied by the "flow resistance" it meets. Therefore, the two standard methods for controlling radial temperature gradients in a rig (hence specimen temperatures) are either

- regulation of the heat flow by electrical heater elements, or
- regulation of the heat flow resistance by variable mixture gas gaps.

Both principles, plus combined heater-gas mixture regulation, have been used in BR2. The advantage of electrical in-pile heaters lies in closer control of the temperature and in the possibility to level reactor-induced axial temperature gradients in the specimens. Gas mixture control, on the other hand, takes up less space in the rig and provides large range regulation with less expensive in-pile and out-pile equipment. Gas regulated rigs do not contain fragile electrical heaters and can be designed for practically any temperature.

3.3.2. 300°C Steel Irradiation.

3.3.2.1. Scope of the Experiment.

Standard Charpy V specimens (10 x 10 x 55 mm) and sub-size specimens (5 x 10 x 55) of mild steel had to be irradiated at about 290°C to integrated fast neutron flux values between 0,5 and 2 x 10^{20} nvt (E above 1 MeV).

3.3.2.2. Solution.

The main problem during the design study stage of the experiment was the thermal layout of the irradiation device. Due to the high nuclear heating in the BR2 core and to a high specimen density, each specimen represents by itself a heat source of 250 to 500 W.

Moreover, the specimen geometry requests a two-dimensional heat transfer from a square source to a cylindrical sink.

Several tentative solutions were considered, including rigs with metal filler pieces and metal oxyde powder as heat transfer medium, and corresponding thermal calculations were carried out.

Finally, only one device appeared to be appropriate, taking into account, that for economy reasons no costly out-pile equipment could be used.

In the rig developed, the specimen column is surrounded by liquid sodium-potassium eutectic alloy which transfers the heat to the specimen carrier (see figure 10). The specimens are arranged in groups of four, they are chamfered on the notch side for easier mounting. The first rig of the 300°C steel series contained five rows of specimens, two of which were tensile specimens contained in hollow shells to fit the "square" geometry of the arrangement. Two Charpy V specimens had been drilled to take up thermocouples with their hot junctions sitting next to the notch root.

The two following rigs contained only Charpy V specimens, partly of the 5x10x55 mm sub-size design.

Table 4 resumes the characteristics of the specimen carriers which have been used.

Table 4.

Specimen Carriers for the 300°C Steel Rigs.

Rig Nr.	Design Stage	Number of groups	Number of Specimens				Number of Thermocouples.
			Charpy 10x10	Charpy 5x10	Tensile	Dummy	
01	MK I	5	16	-	2	2	8
02	MK II	6	12	24	-	-	6
03	MK II	6	-	48	-	-	6

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In all cases, the gas-tight penetrations of the thermocouples into the specimen carrier was achieved by high temperature brazing (see paragraph 3.3.2.3). Thermocouples were Chromel-Alumel with 1 mm O.D. stainless steel sheath.

Heat transfer between the specimen carrier can and the outer capsule tube is achieved mostly by radial fins machined into the can O.D. Only a small percentage flows through the remaining gas gap.

3.3.2.3. Development.

Among the technological problems to be solved, there mainly appeared :

- the NaK filling technique,
- the gas-tight thermocouple penetration,
- the specimen carrier assembly.

Hence, a series of tests proceded the actual rig manufacturing. They are briefly explained hereafter.

Liquid metal handling was practised in a glove box using purified and controlled argon atmosphere. The valve-type filling head (see figures 2 and 10) was developed and the filling procedure carried out on several test cans. It was found that the NaK eutectic, which is liquid at room temperature (freezing point -12°C) but has poor flowing characteristics, can be driven into closed capsules when these are evacuated. This, a special T-piece was made through which the capsule is permanently evacuated while the NaK flows in from a burette.

After the specified quantity has been filled in, the capsule is closed using a metal-to-metal valve arrangement with plate springs. It can then be taken out of the glove box and seal-welded without hazard.

High temperature brazing tests were carried out in order to assess a safe design for the gas-tight penetration of thermocouples into the specimen carrier. The brazed joint had to satisfy the following requirements :
- compatibility with liquid alcali metals up to 400°C,
- helium leak tightness, as brazed and after thermal cycling,
- mechanical strength and corrosion resistance up to 400°C

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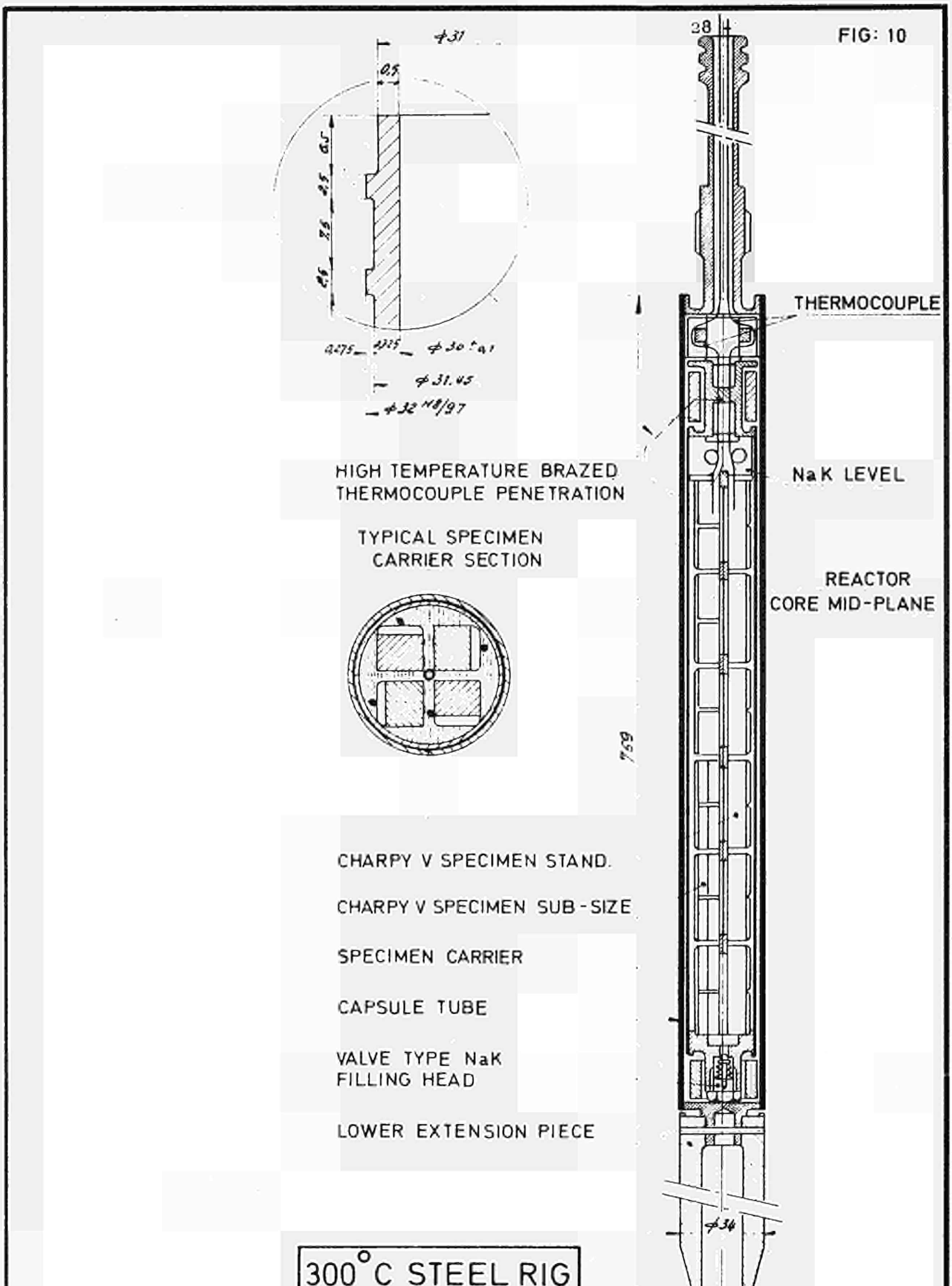

300°C STEEL RIG

Two brazing alloys were mainly used : NICROBRAZ 30 (WALLCOLMONOY Corp., Detroit, Mich.) with 19% Cr, 10% Si, max. 0,15% C and 71% Ni, and N.M.P.1 (ENGELHARD Ind. Ltd, Sutton, Surrey) with 48% Ni, 31% Mn and 21% Pd. The quoted brazing temperatures are 1150° and 1125°C respectively.

Except for the first "pilote" series, all test brazing were carried out under high vacuum (10^{-4} Torr), using an induction furnace. Testing was achieved by visual examination, helium leak probe and metallographic sectioning.

It soon appeared that embrittlement of the thermocouple sheaths, caused by erosion and formation of fragile alloys, was the main problem of the tests. This problem was eventually overcome by close control of the following brazing parameters :
- vacuum (10^{-4} Torr or less),
- clearance between sheaths and basic material (minimum possible),
- brazing temperature (not to exceed the specified limit),
- brazing time (as short as possible).

Reference chromel-alumel thermocouples which were spot welded to the penetration piece recorded the temperature onto a high speed recorder. By appropriate operation of the high frequency generator, the brazing temperature could be reached within ± 5°C, and for a few seconds only.

Further details on the brazing technique will be given in paragraphs 3.3.4.3. and 3.3.5.3. of this report.

For the assembly of the specimen carrier, a mounting jig was developed.

Figure 8 shows the procedure of the specimen carrier assembly.

The arrangement was kept in a trough under a flow of dry nitrogen in order to limit specimen corrosion.

Details of the gas line and thermocouple connections in the rig head are shown on figures 11 and 12.

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3.3.2.4. Irradiation.

The first rig was irradiated during 15,3 days in a five plate fuel element without support tube, resulting in an integrated fast flux in the specimens (E above 1 MeV) of 1,5 to 1,9 x 10^{20} nvt.

Temperature readings were between 50 and 100°C above the calculated values. This was probably due to an error in the estimation of the heat transfer contact resistance between specimen carrier and outer capsule tube. Calculations later showed that the contact resistance was about 0,5°C/W/cm^2. This value was taken into account for the Mark II design stage (rigs nr. 02 and 03).

The second rig was irradiated during 8,1 days, resulting in a dose of 0,7 to 0,9 x 10^{20} nvt (E above 1 MeV), whereas rig nr. 03 accumulated 1,2 to 2 x 10^{20} nvt in 15,8 days. Irradiation temperatures were between 250° and 320°C.

Except for one thermocouple which had failed during a late stage of rig nr. 03 assembly, thermocouples in all three rigs performed satisfactorily.

3.3.2.5. Post-Irradiation Work.

Dismantling of the rigs had been practised on a dummy specimen carrier fitted with spare specimens and with stainless steel wires to simulate the thermocouples. Both brazing and NaK filling procedure corresponded to the techniques developed for the actual rig.

Hot laboratory work included impact testing, hardness measurements, as well as tensile testing of two specimens.

3.3.3. 750°C Graphite Irradiation.

3.3.3.1. Scope of the Experiment.

Graphite specimens had to be irradiated under 750°C, to integrated neutron flux values between 1,3 and 2 x 10^{21} nvt (E above 0,1 MeV) with stringent limitations for temperature deviations in space and time from the nominal.

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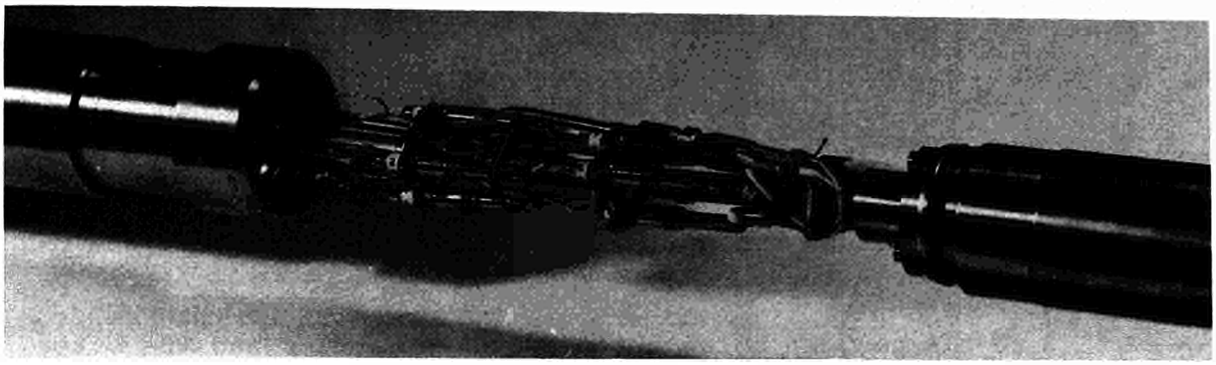

Figure 11.

300°C Steel Rig.

Gas Line and Thermocouple Connections in the Rig Head.

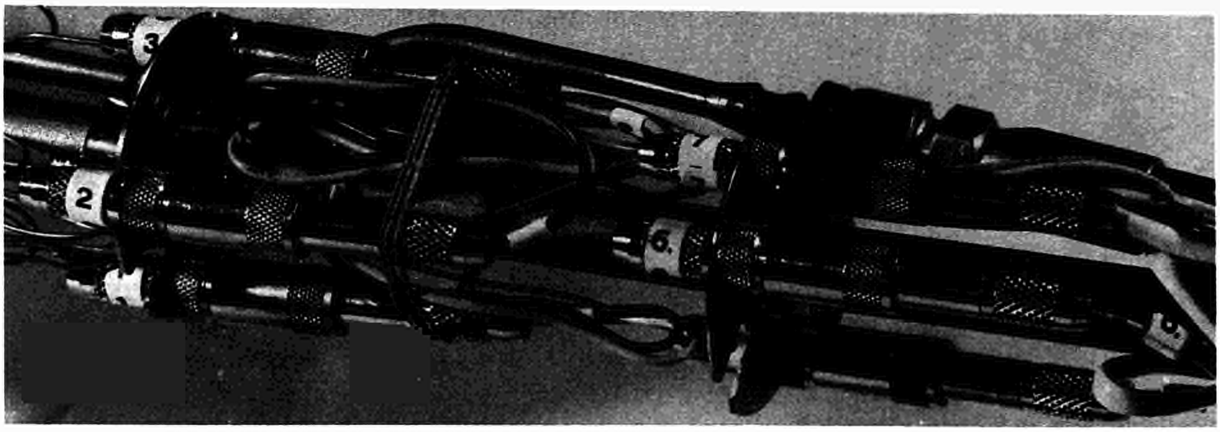

Figure 12.

750°C Graphite Rig

Items Before Assembly.

Figure 13.

3.3.3.2. Solution.

The irradiation device which was studied and designed in collaboration with the experimenter and an external company, features four groups of specimens mounted into graphite barrels (see figure 14).

One common gas-tight specimen carrier can houses the four groups.

A gas gap between the specimen carrier and the outer capsule tube defines the heat transfer from the specimens, and hence their temperatures.

The appropriate gas mixture (He-N_2) enters through a capillary tube running through the specimen carrier. The mixture is set to the He-N_2 ratio required by means of a control console receiving the signal from a thermocouple in the top specimen group.

The three remaining groups are fitted with electrical heaters which are controlled by independent circuits from an electrical control panel.

3.3.3.3. Rig Manufacturing.

One completed rig and the items for three subsequent assemblies have been purchased from an exterior company. Figure 13 shown most of the detail pieces before assembly wrapped in plastic bags. Not shows are the specimens and the suspension tube (upper extension piece).

Rig assembly has been practised on a dummy specimen carrier with stainless steel wires simulating thermocouples and heater elements.
Again, high temperature brazing was used to achieve the gas-tight penetration the carrier of six thermocouples, six heater leads and one capillary tube.

3.3.3.4. Irradiation.

Two rigs have been irradiated, two more will follow. Figure 16 shows a view onto the reactor top cover with the rig in its irradiation position.

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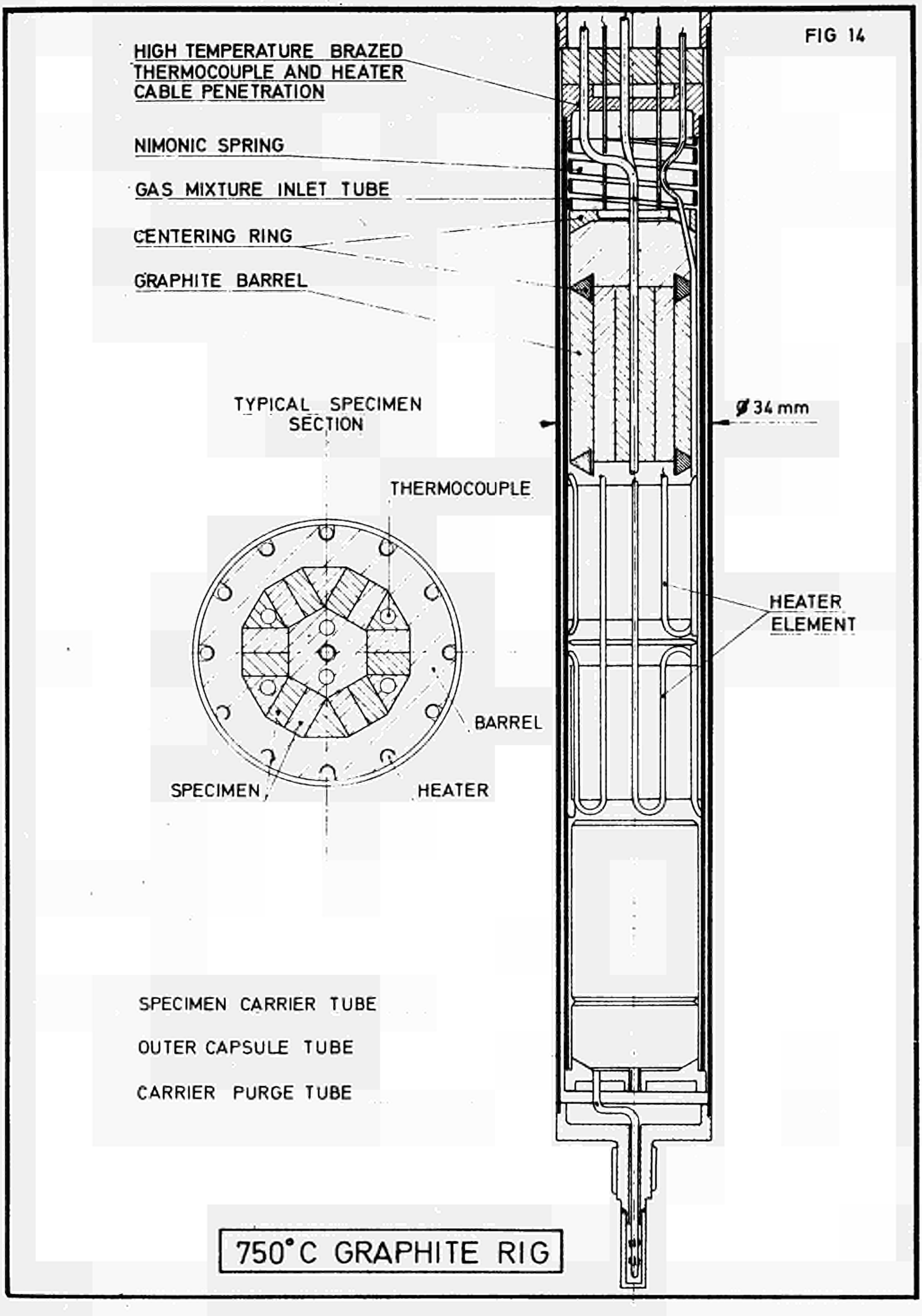
FIG 14
HIGH TEMPERATURE BRAZED THERMOCOUPLE AND HEATER CABLE PENETRATION
NIMONIC SPRING
GAS MIXTURE INLET TUBE
CENTERING RING
GRAPHITE BARREL
TYPICAL SPECIMEN SECTION
THERMOCOUPLE
BARREL
SPECIMEN
HEATER
Ø 34 mm
HEATER ELEMENT
SPECIMEN CARRIER TUBE
OUTER CAPSULE TUBE
CARRIER PURGE TUBE
750°C GRAPHITE RIG

The general thermal behaviour was quite satisfactory as the specified temperatures could be kept within ± 5°C over 80% of the total irradiation time. Each rig was irradiated to 1,3 ... 1,5 x 10^{21} nvt (E above 0,1 MeV) taking 41,7 days for the first and 46,9 days for the second device.

In rig nr. 1, one heater element failed towards the end of the irradiation, whereas all thermocouples survived. In rig nr. 2, one heater failed as well towards the end of the irradiation. One thermocouple was defect right in the beginning and two others failed during the irradiation. In all cases, no serious effect on temperature control occured.

3.3.3.5. Dismantling.

The delicate work of recovering a large number of rather fragile specimens had been practised by dismantling the dummy specimen carrier. Only one specimen was broken per rig.

The activity of the irradiated specimens was much higher than expected, resulting in surface beta-gamma doses up to 250 mrem/h (mainly Cr-51) on certain pieces after two months cooling time. Cross-checking showed that the activity is not due to surface contamination during dismantling in the hot cell.

For the moment no definite explanation for this phenomenon is available.

3.3.4. 1000°C Fuel Ball Irradiation.

3.3.4.1. Scope of the Experiment.

Two spherical fuel elements with 60 mm O.D. had to be irradiated with about 2,5 kW fission power and 1000°C surface temperature.

The irradiation time desired was about 20 days.

Figure 15.

750°C Graphite Rig
View on the Reactor Top Cover
The Rig in its Irradiation Position.

Figure 16.
1000°C Fuel Ball Rig
Test Brazing of a Thermocouple
Penetration

Enlargement ≈ 4x.

3.3.4.2. Solution.

Figure 17 represents the specimen carrier section of the rig. Each carrier is made up from a gas-tight stainless steel can, filled with helium and containing a split graphite cylinder. The fuel ball is placed inside the spherical cavity of the cylinder and kept to the desired gas gap distance by ceramic spacer pins. Table 5 explains the positions of the seven thermocouples.

Table 5.

Thermocouple Arrangement in the 1000°C Fuel Ball Rig.

Fuel Ball Carrier	Thermocouple Nr.	Thermocouple Position
Upper	1	Fuel ball surface
	2	Graphite cylinder
	3	Fuel ball surface
	4	Graphite cylinder
	5	Fuel ball surface
Lower	6	Fuel ball surface
	7	Fuel ball surface

All thermocouples were chromel-alumel with 1 mm O.D. stainless steel sheath.

The outer capsule envelope is made up from a thick-walled aluminium tube with milled slots on the I.D., housing thermocouple wires and the gas inlet tube. A gas gap between steel can and aluminium envelope fixes the heat transfer resistance by variable helium-nitrogen mixture which is preset in the out-pile gas mixing panel.

Figure 18 shows the thermal characteristics for one specimen can of the irradiation device. The total heat transfer through inner and outer gas gap is plotted against the temperature of the inner capsule (specimen can). In order to trace the diagram, the following simplifications have been introduced :

- there is a constant ratio between the energy transferred from the fuel ball to the inner capsule and the energy transferred from the inner capsule to the aluminium envelope.

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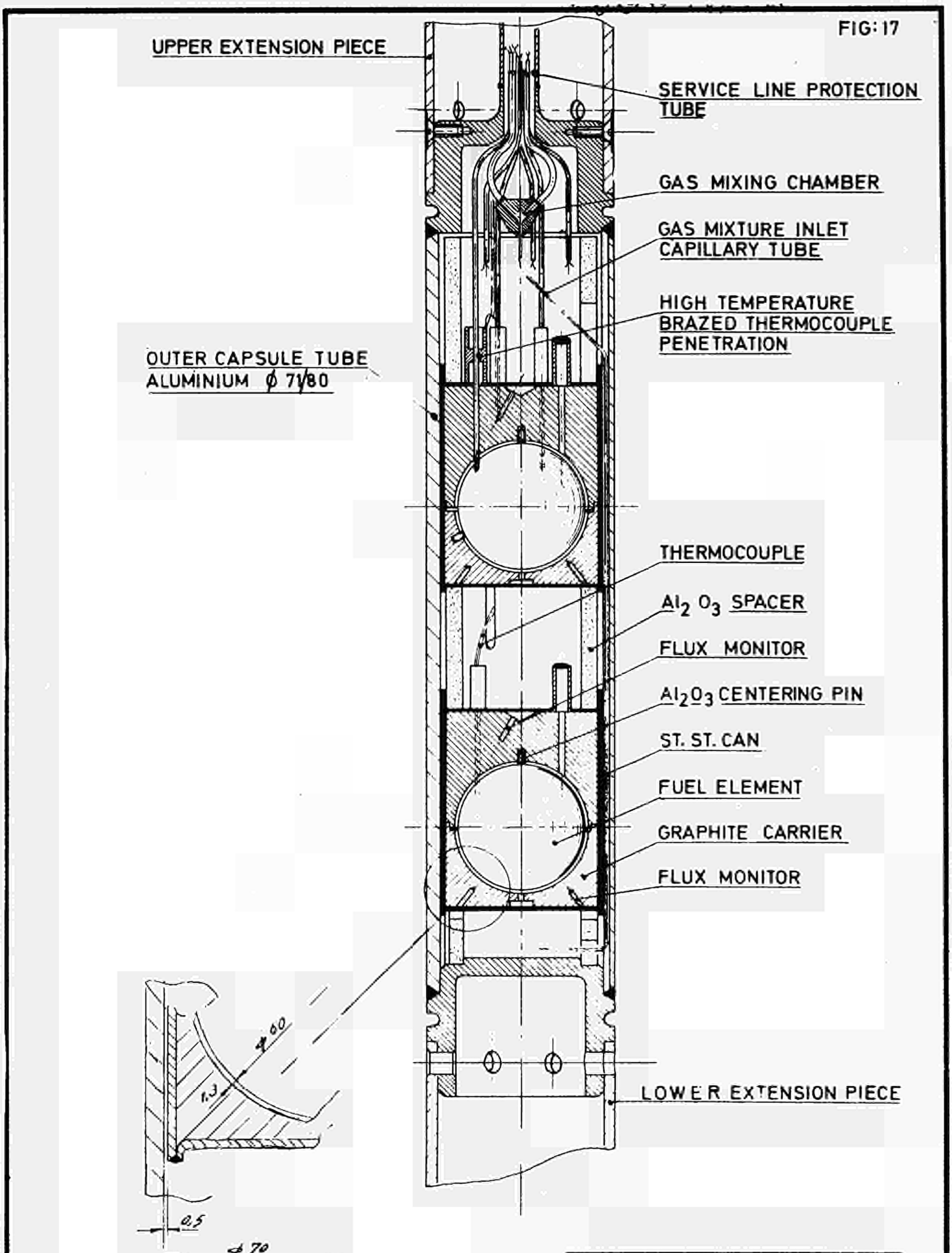

1000°FUEL BALL RIG

This ratio has been taken to 0,8 considering the nuclear heating in the irradiation position envisaged.
- heat transfer through the outer gas gap is uniformly distributed over the entire can length.
- the temperature drop through the stainless steel can wall is constant.
- the aluminium wall temperature is constant.

The diagram shows that 1000°C surface temperature on the fuel sphere can be maintained for a total sphere heat output between 1840 W (pure N_2) and 2760 W (pure He), resulting in a regulation width of 33% of the maximum admissible power output.

3.3.4.3. Rig Manufacturing.

The problem of the gas-tight thermocouple penetration into the specimen can was solved by high-temperature brazing of the sheaths to special sleeves which, in turn, were welded to the cover.*) Figure 16 shows a test sleeve after successful brazing. The four pads are clamped onto the thermocouple sheath before brazing in order to protect the fragile sheath against bending.

Most of the graphite handling was carried out in a glove box under helium atmosphere in order to limit the contamination with air and moisture (see figure 19). To the same end, the specimen carrier was heated to 400°C under protective atmosphere after assembly, evacuated and back-filled several times with helium.

3.3.4.4. Irradiation.

A nuclear model had been manufactured to measure the rig "self-shielding" coefficient. The model consisted of a split graphite cylinder filled with boron-graphite powder simulating the fuel. The graphite cylinder was mounted into a stainless steel can which in turn was sitting in an outer aluminium tube. All components of the model simulated those of the actual irradiation rig full scale.

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*) Figure 20 represents a micrographic section of a test piece (stainless steel sheath, NICROBRAZ 30) which has been overheated during the brazing. The sheath was broken on either side of the penetration after recovery of the assembly from the furnace. It can be seen that substantial erosion of the sheath had occured.

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THERMAL CHARACTERISTICS OF THE FUEL BALL CAPSULE.

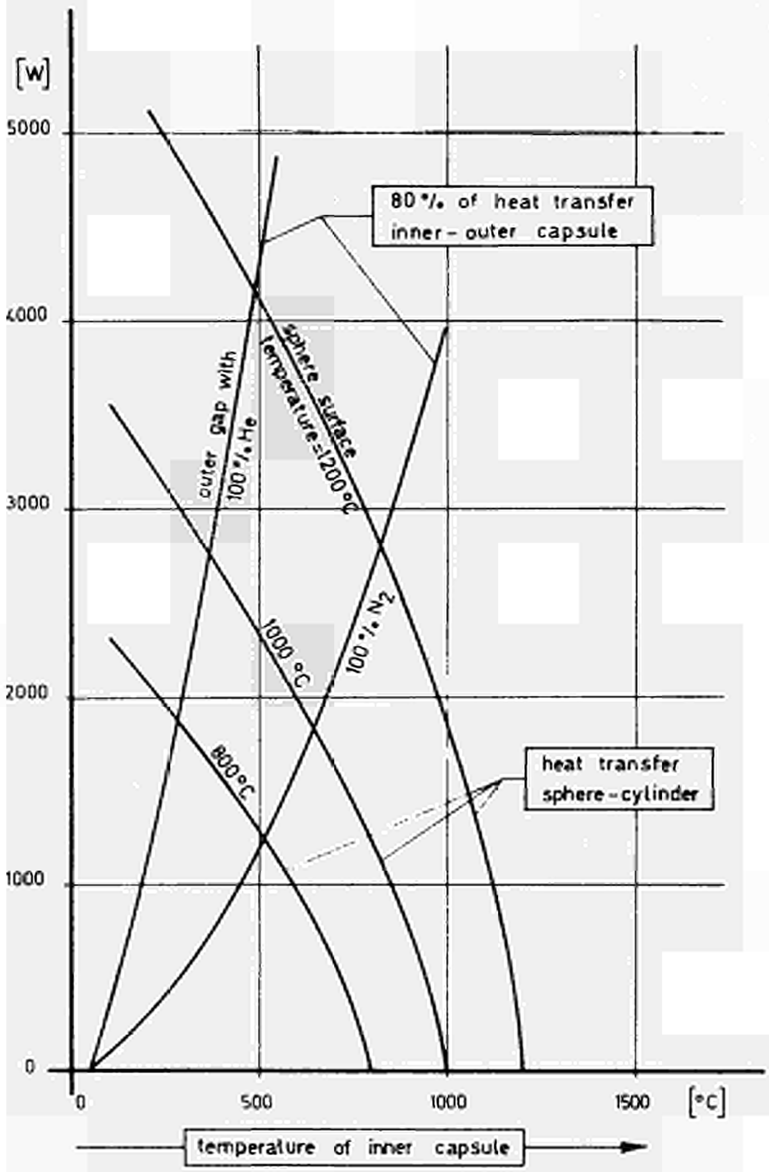

Figure 18.

Neutron flux detectors were placed into the graphite-boron sphere as well as into places of the cylinder corresponding to those of the future irradiation rig.

The nuclear model was irradiated in BR2 during a low power run. The analysis of the flux detectors yielded a predicted perturbed thermal neutron flux of 1,2 to 1,4 x 10^{14} n/cm^2 s.

The rig was then irradiated in the BR2 L 240 reflector position for a total duration of 26,3 days. The fuel ball surface temperatures came well into the specified range (round 1000°C) and all thermocouples kept working through the whole irradiation.

3.3.5. 1250°C Fuel Particle Irradiation.

3.3.5.1. Scope of the Experiment.

Fuel particles for a high temperature gas cooled reactor concept had to be irradiated under 1250°C, to high burn-up of the initial fissile material quantity and to a substantial dose of fast neutrons. Temperature control and neutron flux dosimetry was specified.

3.3.5.2. Solution.

The irradiation device designed (see figure 21) contains two specimen carrier cans. The upper can houses three high temperature thermocouples and a reference chromel-alumel "cool" thermocouple.

The specimens are contained in a cylindrical graphite matrix mounted into the can by means of niobium spacers and axial ceramic insulation spacers. A 1 mm helium gap separates the matrix from the can. The outer gas gap between the can and the aluminium shell is used for temperature control by variable gas mixture (He-N_2 or He-Ne). Figure 23 shows the thermal characteristics of the rig by means of a diagram similar to figure 18. It can be seen that the regulation width is slighly more limited as compared to the fuel ball rig (30% of the maximum power output for 1200°C matrix temperature), due to a narrow outer gas gap. This layout had to be chosen in order to keep the stainless steel can temperature within safe limits.

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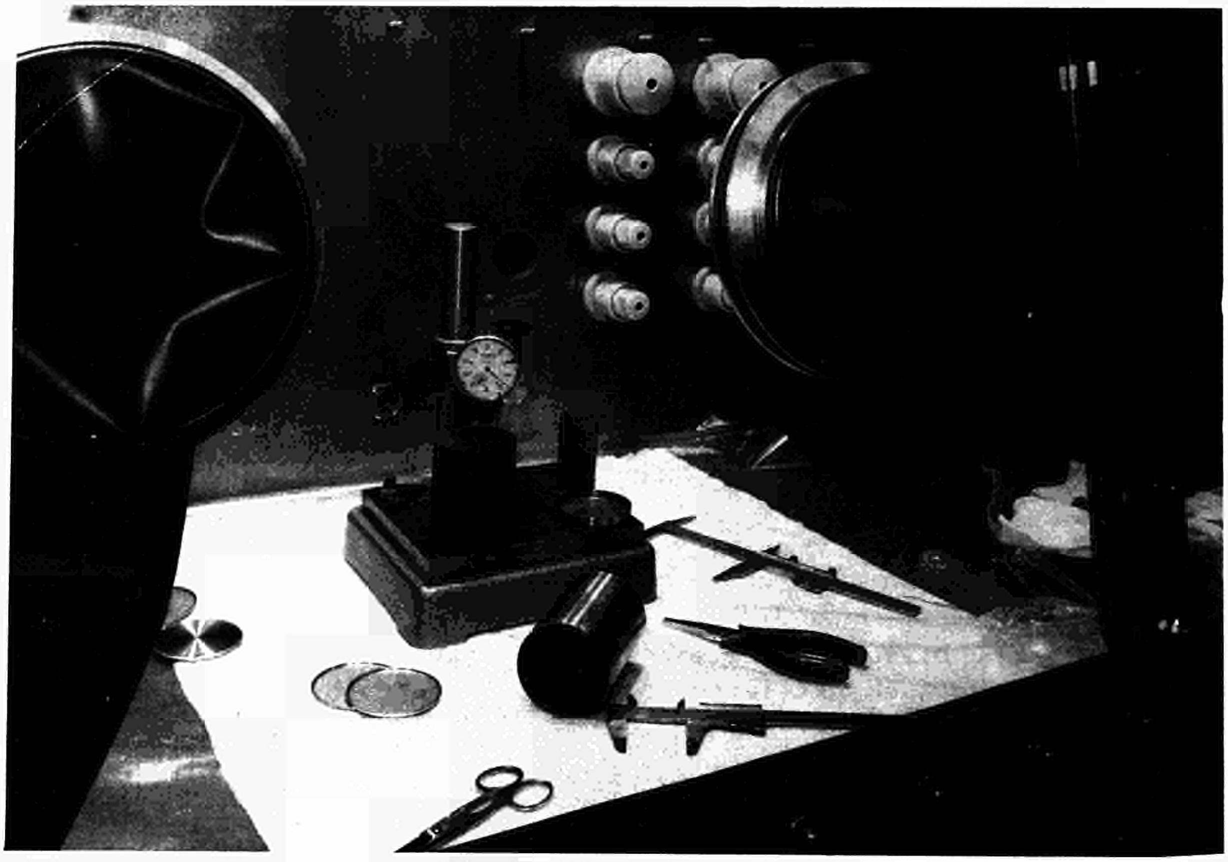

Figure 19.

Graphite Handling in a Glove Box.

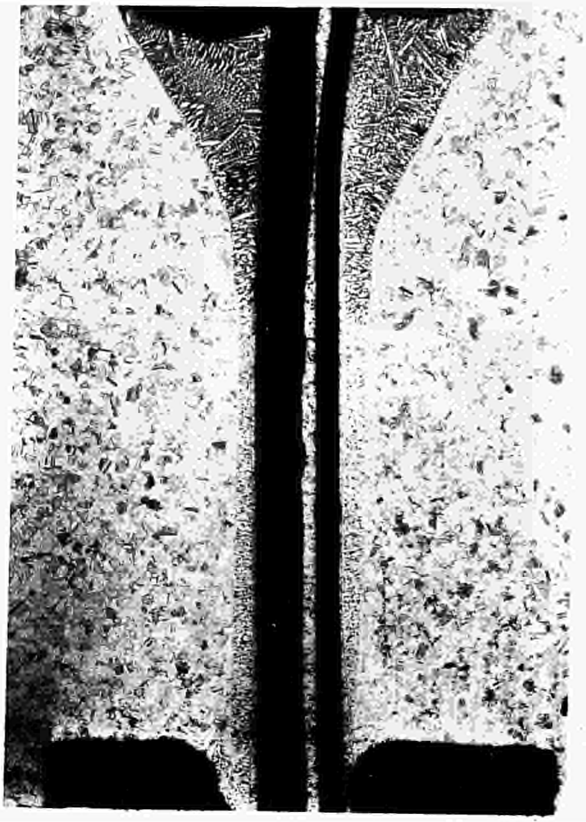

Figure 20.

Test Brazing of a Thermocouple Penetration

Microphotography of the Test Piece.
(enlargement 15x).

Heavy Sheath Erosion due to Overheating

Platinum/Platinum-Rhodium and Tungsten-Rhenium/Tungsten-Rhenium thermocouples were selected for temperature measurement inside the graphite matrix.

3.3.5.3. Rig Manufacturing.

Apart from supply difficulties of high temperature thermocouples to BR2 specifications, the gas-tight brazed joints between thermocouple sheaths and specimen carrier can offered the main technological problem. Once more, induction furnace brazing under high vacuum was applied, using NICROBRAZ 30* alloy and electrolytic copper. Materials successfully brazed to stainless steel (AISI 304) were :

- Platinum - 2% Mo,
- Niobium,
- Niobium - 1% Zr,
- Tantalum.

Diffusion tests at 900°C after brazing showed, however, embrittlement of the joint for the Pt - 2% Mo and the Ta sheaths.

Figure 24 shows a part of the thermocouple brazing assembly which goes into a vertical quartz tube. Figure 25 shows a close-up view of a successfully brazed joint with the three thermocouples penetrating the center opening of the can end cap. An auxiliary support rod can be seen, as well as a chromel-alumel brazing temperature control thermocouple.

3.3.5.4. Irradiation.

Two rigs have been assembled and loaded into BR2 fuel element positions. The first one was irradiated for 4,5 reactor cycles (about 90 days), the second is still under irradiation.

Most of the thermocouples failed before the scheduled end of the irradiation, by open circuits. The history of the thermocouples, as far as known up to April, 1967, is given in table 6.

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* Trade mark.

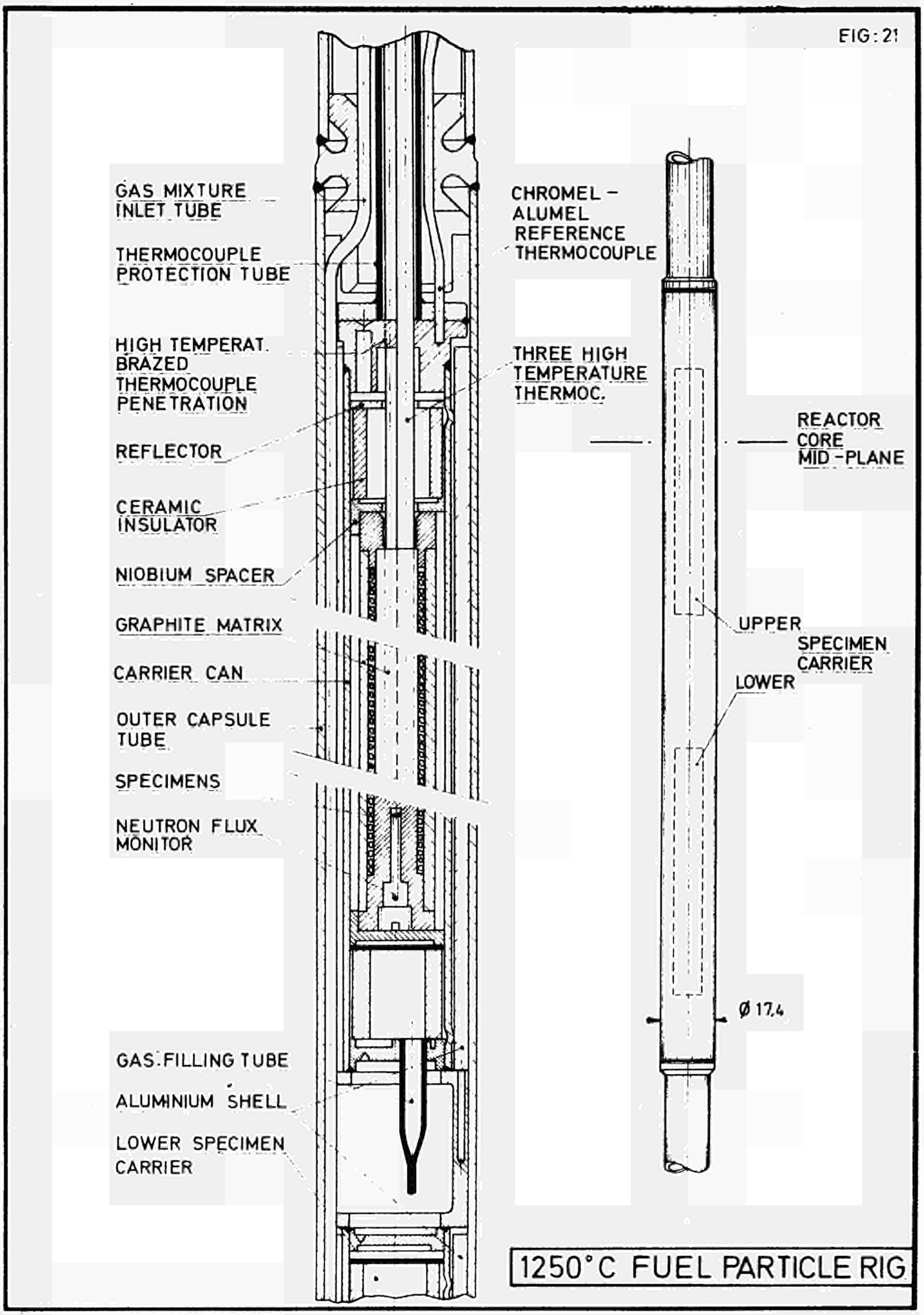
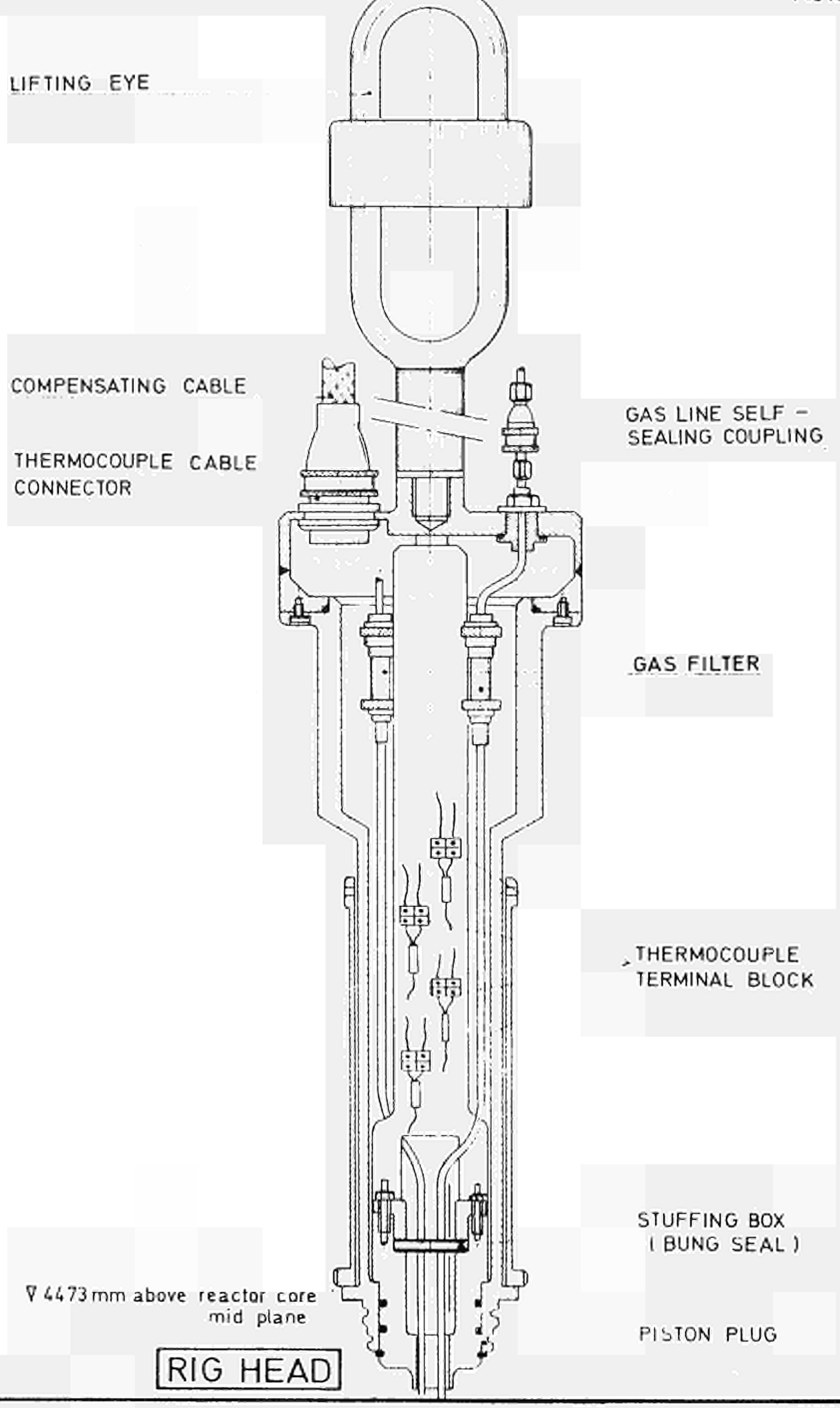


FIG: 21
GAS MIXTURE INLET TUBE
THERMOCOUPLE PROTECTION TUBE
HIGH TEMPERAT. BRAZED THERMOCOUPLE PENETRATION
REFLECTOR
CERAMIC INSULATOR
NIOBIUM SPACER
GRAPHITE MATRIX
CARRIER CAN
OUTER CAPSULE TUBE
SPECIMENS
NEUTRON FLUX MONITOR
GAS FILLING TUBE
ALUMINIUM SHELL
LOWER SPECIMEN CARRIER
CHROMEL - ALUMEL REFERENCE THERMOCOUPLE
THREE HIGH TEMPERATURE THERMOC.
REACTOR CORE MID-PLANE
UPPER
SPECIMEN CARRIER
LOWER
Ø 17.4
1250°C FUEL PARTICLE RIG

FIG. 22



RIG HEAD

THERMAL CHARACTERISTICS OF THE 1250 °C COATED FUEL PARTICLE RIG.

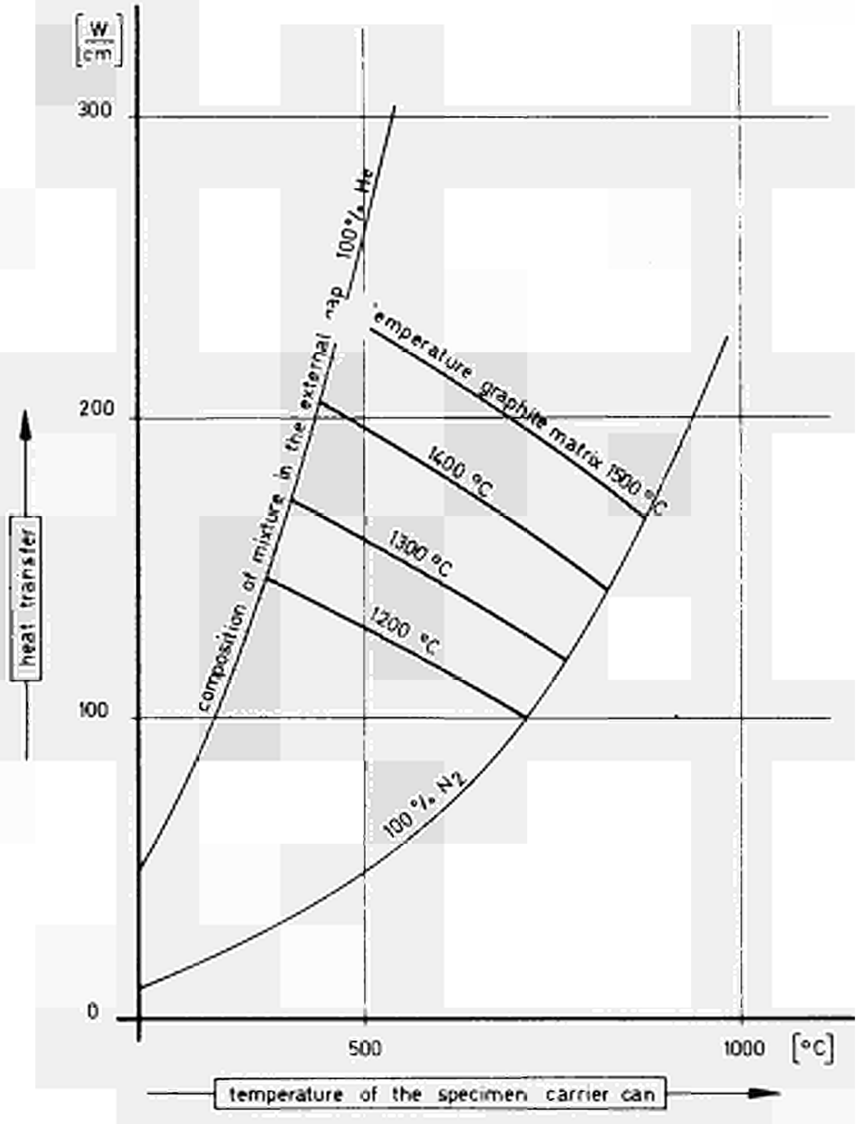


Figure 23

Table 6.

Thermocouple History of the 1250°C Fuel Particle Rigs.

T/C Nr.	Wire Material	Sheath Material	Sheath O.D. (mm)	Sheath Length (mm)	Extensions Wire	Extensions Sheath	Approximate irradiation time before failure (days)
1	W 5 Re/ W 26 Re	Nb 1 Zr	1,0	756	W 5 Re/ W 26 Re	St. St.	20
2	W 5 Re/ W 26 Re	Mo (internal) Nb (external)	1,45	789	W 5 Re W 26 Re	St. St.	56
3	Pt/Pt 10 Rh	Nb 1 Zr	1,45	780		St. St.	30
4	W 5 Re/ W 26 Re	Nb 1 Zr	1	798	W 5 Re/ W 26 Re	St. St.	
5	W 5 Re/ W 26 Re	Inconel 702 (internal) Pt (external)	1,65	315	(conti- nuous)	Inconel 702 conti- nuous	
6	Pt/Pt 13 Rh	Pt	1,65	430	(conti- nuous)	St. St.	9

Temperatures have generally been between 1200°C and 1300°C, but the small regulation width of the gas mixture control required frequent changes of the irradiation position to compensate the considerable consumption of fissile material in the rigs.

4. References.

1. " Belgian Engineering Test Reactor BR2. Safety and Design". BLG 59.
2. " The BR2 Testing Reactor and its Connected Laboratories. Annual Progress Report 1964 ". EUR 2625.e.

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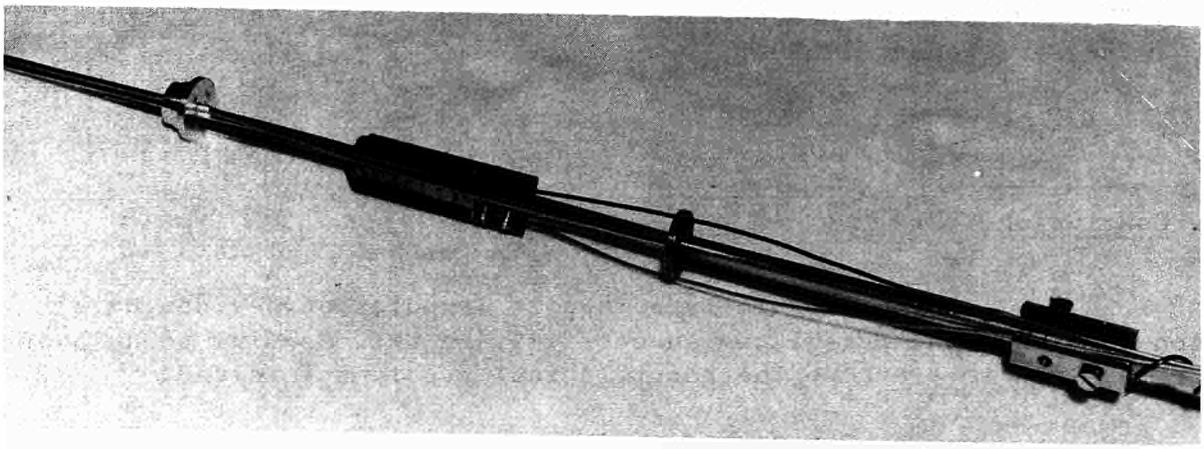


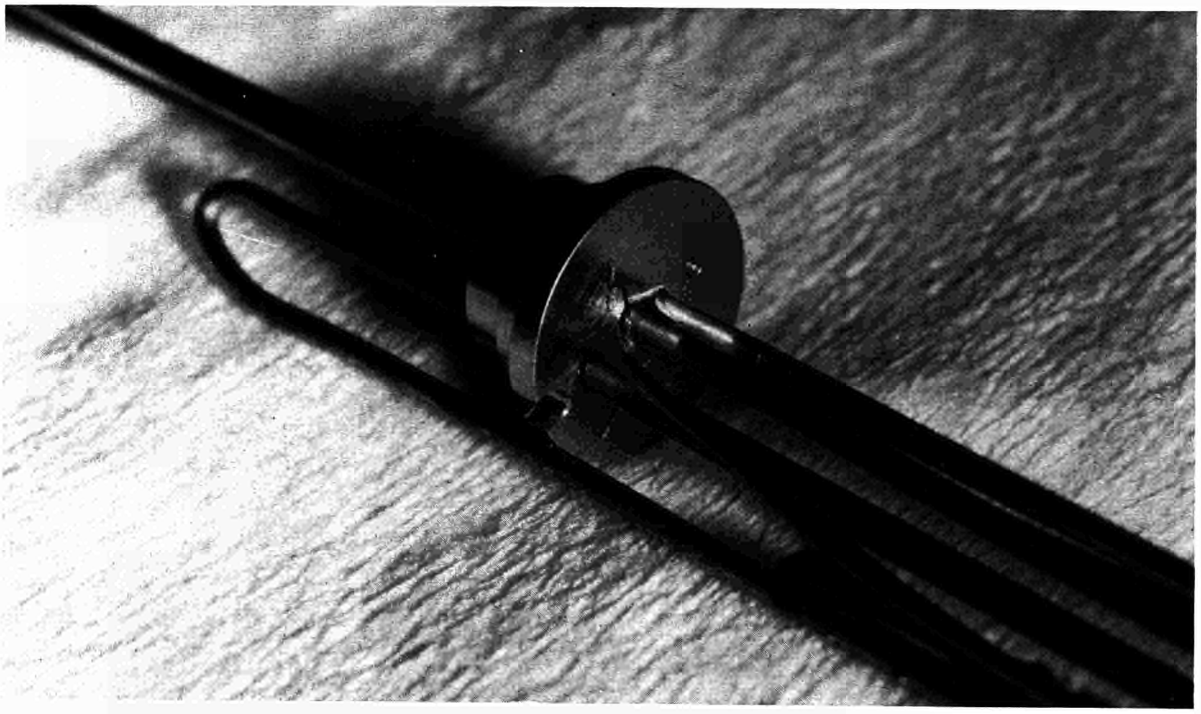
Figure 24.

Thermocouple Brazing Assembly.

1250°C Fuel Particle Rig.

Figure 25.

Brazed Joint.



3. "The BR2 Testing Reactor and its Connected Laboratories. Annual Progress Report 1965".
EUR 3138.e.

5. Conclusion.

Capsule-type in-pile irradiation devices have been developed and irradiated successfully in BR2. Special techniques were applied to overcome the technological problems involved.

The work described could be performed due to the support and advise given by Mr. STIENNON, Head of the Joint BR2 Operating Group, and by Mr. PLANQUART, Head of the Technology Department.

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Alfred Nobel

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